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Risk Assessment of *Bythotrephes longimanus* establishment in Muskoka Lakes: an Assessment of QBRAT, the Quantitative Biological Risk Assessment Tool

Évaluation du risque posé par l'établissement de *Bythotrephes longimanus* dans les lacs Muskoka : examen de l'outil de quantification du risque biologique (OQRB)

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Abstract

The purpose of this risk assessment exercise was to examine the usefulness and limitations of QBRAT v2 and provide feedback to the creators. In so doing, I developed a risk assessment based on the question: 'What is the probability of establishment, with negative impacts, of *Bythotrephes longimanus* in Muskoka Lakes next year (2006)?' I specifically addressed the EB2 watershed as topographical and invasion data were available from Norm Yan, Allegra Cairns and Melisa Elliot (York University). This is a very specific use of the QBRAT model, as it turned out, and avoided many of the problems associated with trying to quantify impacts and costs. It did highlight the flexibility and quantitative nature of the model. The v2 model contains four sequential steps in the invasion process: arrival, survival, establishment and spread. However, these boxes can be used to estimate the cumulative probability of any sequence to a maximum of four steps, provided that each is independent of the others. If variables are not independent, the resultant interactions need to be calculated outside of QBRAT and the final independent variable used in the program. The four steps considered in the *Bythotrephes* risk assessment were the probability of arrival, survival of the individual, establishment related to propagule pressure, and establishment related to mortality. Each of these is the result of a complex set of variables and QBRAT could be redefined to estimate the probability of these processes as well.

Risk assessment often involves the assessment of different management options or conditions. QBRAT v2 can only consider one set of conditions which means that the data must be systematically changed and the program run numerous times in order to evaluate multiple scenarios. It is recommended that a front end and back end be constructed so that multiple scenarios can be examined at a time and that the resultant data be accumulated in a logical manner in an output file which opens on completion of the run. Presently, an output file is created for each run and is not open on completion of the run. The output from the program could be made more user friendly if the numeric values (e.g. probabilities etc) could be presented in a table which could be more easily read and copied for use in other programs.

The great strength of QBRAT is the inclusion of confidence information, which can be input as a quantitative number or ranked estimate, and the flexibility given to the programmer to define the characteristics of these estimates. This means that the final confidence distributions and sensitivity analysis around the cumulative risks are more informative for guiding management actions.

The *Bythotrephes* risk assessment indicated that 82% of all lakes were likely to experience severe impacts if *Bythotrephes* arrived. The probability of arrival at a lake was dependent on the shape of the function describing lake accessibility : the rate of invasion was nearly half if the scale was linear compared with logarithmic. The impact of compliance with boating regulations (washing of boats and gear when moving between lakes) was signigicant : roughly a third the number of lakes were invaded at 80% compliance compared with 40% compliance. Sensitivity analyses indicate that the projections of newly invaded lakes were most sensitive to the value of P1 (arrival), and this sensitivity increased as lakes became less accessible. High access lakes were equally sensitive to the seasonal patterns in boat traffic.

Résumé

Le but du présent exercice d'évaluation du risque est de faire l'examen de l'OQRB v2 pour en déterminer les forces et les faiblesses et fournir une rétroaction à ses créateurs. L'évaluation du risque que j'ai menée aux fins du processus d'examen de l'OQRB v2 s'articule autour de la question suivante : Quelle est la probabilité d'établissement de *Bythotrephes longimanus*, avec tous ses effets négatifs connexes, dans les lacs Muskoka au cours de la prochaine année (2006)? Mon évaluation du risque porte expressément sur le bassin hydrographique EB2, car je disposais de données sur la topographie et l'envahissement de ce bassin fournies par Norm Yan, Allegra Cairns et Melisa Elliot (Université York). Il s'agit d'une utilisation très restreinte du modèle OQRB qui m'a permis d'éviter nombre des problèmes que posent les tentatives de quantification des effets et des coûts. Cet exercice fait ressortir la souplesse d'utilisation et la nature quantitative du modèle. Le modèle v2 reproduit un processus d'envahissement en quatre étapes séquentielles, c'est-à-dire l'arrivée, la survie, l'établissement et la propagation. Cependant, les champs de données réservées à ces étapes peuvent servir à estimer la probabilité cumulée de n'importe quelle séquence comportant au plus quatre étapes, à la condition que chacune d'elle soit indépendante des autres. Si les variables ne sont pas indépendantes, le calcul des interactions résultantes doit se faire en dehors de l'OQRB, et la variable indépendante finale peut être utilisée dans le programme. Les quatre étapes du processus d'envahissement prises en considération dans l'évaluation du risque posé par *Bythotrephes* sont les suivantes : la probabilité d'arrivée, la survie des individus, l'établissement lié à la pression des propagules et l'établissement lié à la mortalité. Chacune de ces étapes est le résultat d'un ensemble complexe de variables; l'OQRB pourrait également être redéfini pour estimer la probabilité de chacune d'elles.

L'évaluation du risque nécessite souvent l'évaluation de différentes options ou conditions de gestion. L'OQRB v2 ne peut évaluer qu'un seul ensemble de conditions, ce qui nécessite un changement systématique de données et l'exécution de nombreux passages du programme pour évaluer des scénarios multiples. La mise au point d'interfaces dorsale et frontale est recommandée pour permettre l'examen simultané de scénarios multiples et le stockage des données résultantes selon une structure logique dans un fichier de sortie qui s'ouvre une fois le passage exécuté. Actuellement, un fichier de sortie est créé pour chaque passage, mais il ne s'ouvre pas une fois le passage exécuté. La sortie du programme pourrait être plus conviviale si les valeurs numériques (probabilités, etc.) étaient présentées sous la forme d'un tableau pouvant être plus facilement lu et copié pour être utilisé dans d'autres programmes.

La grande force de l'OQRB découle, d'une part, de l'inclusion d'éléments d'information sur les niveaux de confiance qui peuvent être entrés sous la forme de nombres quantitatifs ou d'estimations ordonnées et, d'autre part, de la marge de manœuvre qu'il offre au programmeur pour définir les caractéristiques de ces estimations. Cela signifie que les distributions de niveaux de confiance et les analyses de sensibilité finales entourant les risques cumulatifs ont une meilleure valeur informative pour orienter les gestionnaires.

L'évaluation du risque posé par *Bythotrephes* indique que 82 % de tous les lacs sont susceptibles d'être fortement affectés par l'arrivée de *Bythotrephes*. La probabilité d'arrivée de *Bythotrephes* dans un lac est fonction de la forme de la fonction décrivant l'accessibilité du lac : le taux d'envahissement est presque moitié moindre si l'échelle est

linéaire plutôt que logarithmique. L'effet de la conformité aux règlements sur la navigation (lavage des embarcations et de l'équipement au moment de leur déplacement entre les lacs) est significatif : en gros, le nombre de lacs envahis est réduit du tiers avec un taux de conformité de 80 % par rapport à un taux de conformité de 40 %. Les analyses de sensibilité indiquent que les projections relatives aux lacs nouvellement envahis sont plus sensibles à la valeur P1 (arrivée) et que cette sensibilité s'accroît lorsque les lacs deviennent moins accessibles. Les lacs largement accessibles sont tout aussi sensibles aux profils saisonniers liés à la circulation maritime.

Introduction

The purpose of the exercise is to evaluate the workings and usefulness of the Quantitative Biological Risk Assessment Technique 'QBRAT' developed by Marten Koops and Becky Cudmore of the Department of Fisheries and Oceans. QBRAT is a process which assists quantifying and assembling probabilities and their known or estimated certainty within a decision tree design. Using such a tool (a) ensures the math is done correctly, but (b) more importantly, eliminates the weighting of qualitative assignment of ranks and their varying assembly rules. The present risk assessment, developed to conceptualize the *Bythotrephes longimanus* establishment in the Muskoka Region of Central Ontario, was used to evaluate the usefulness of the QBRAT program in risk assessment and in providing guidance to management actions.

QBRAT is set up to assess the likelihood, biological risks, and management costs of a process which involves sequential steps – in the case of invasive species these are usually the arrival, survival, establishment and potential expansion of the species. *B. longimanus*, a large predatory cladoceran, has already invaded the Great Lakes several times (Berg *et al.* 2002). It is presently invading the inland lakes in the Muskoka and Haliburton Regions as well as points west. What I do not know is whether it will successfully invade all lakes or whether access, compliance of the public with deterrents, water quality, food or predation differences amongst lakes will affect the establishment success of this species. Consequently, this risk assessment concerns the probability of establishment in Muskoka lakes and I ask the question:

What is the probability of establishment with negative impacts of *Bythotrephes longimanus* in Muskoka lakes next year?

Here I need to define the endpoints of the assessment as they relate to establishment and to negative effects. *B. longimanus* is a formidable predator which preferentially feeds on cladocerans and, when those are lacking, on small copepods (Vanderploeg *et al.* 1993, Shulz and Yurista 1995, 1999). In the Great Lakes and inland lakes, it has caused zooplankton population declines, extirpation of smaller cladoceran species, and alterations in the migratory behaviour of its prey (Lehman and Caceres 1993; Yan and Pawson 1997; Barbiero and Tuchman 2003; Peacor and Pangle 2006). The prey move to avoid *B. longimanus* by descending into deeper, colder, darker habitat during the day. Irrespective of whether the food supply is appropriate for them at these depths, the colder temperatures greatly increase their egg development times and reduce their productivity. Pangle *et al.* (2007) estimated that these non-lethal effects of *B. longimanus* on its prey were more detrimental to the prey populations than the mortality inflicted by the predator. (However, if the prey had remained in the surface waters, the mortality inflicted would have been much worse – a choice between two evils.) At some point, *B. longimanus* predation is intense enough to eliminate most cladoceran species. Thus, when *B. longimanus* is well established in a lake, I see a marked decline in species richness (Makarewicz *et al.* 1995; Yan *et al.* 2002; Boudreau and Yan 2003). *Daphnia galeata mendotae* and *Holopedium gibberum* (at least in inland lakes (Yan and Pawson 1997) can co-exist with *B. longimanus*. Under these conditions, the remaining prey species suffer reduced production associated with diel migrations. This is the worst scenario – full establishment of *B. longimanus* and devastation of the zooplankton community. This does not always occur when *B. longimanus* invades. Alewife in Lake Ontario have kept the population of *B. longimanus* so low that they are rarely seen (Johannsson *et al.* 1991) – a situation also observed in European lakes; although the

predator is not alewife (Vekhov, 1987 in Spikes *et al.* 2002). Intermediate situations have also been observed where the *Bythotrephes* population is present but the cladocerans have not been eliminated (eastern basin of Lake Erie 1993, 1994 in Dahl *et al.* 1994 and Graham *et al.* 1995). In this instance, they were likely depressed by a population of starving smelt. A strongly skewed negative relationship has been observed between *Bythotrephes* biomass and the biomass of various cladoceran prey (Lehman and Caceres 1993; Johannsson and Graham, Fisheries and Oceans, Canada, unpublished data) (Fig. 1). The cut off densities for the Lake Erie species appeared to be <10 $mg.m^{-2}$ for *Daphnia longiremis*, <50 $mg.m^{-2}$ for *D. retrocurva* and <160 $mg.m^{-2}$ for *Bosmina spp.*

The ripple effects through the food web may be extensive and may affect fish community composition through both competition with young-of-year (YOY) fish and edibility to planktivores. Some young-of-year fish species, which would normally eat zooplankton, avoid *B. longimanus* until they are >70 mm total length (Barnhisel & Harvey, 1995). Does the changed biomass, species composition or distribution of the new zooplankton community affect their growth? It has not been determined. Other YOY fish eat *B. longimanus* and suffer gut punctures from the tail spines (Compton and Kerfoot 2004). Is this lethal? Does it reduce feeding and growth rates? Still other YOY fish have figured out that they can eat *B. longimanus* and leave the spine behind (smelt) and their growth rate is good when this prey is present (Parker *et al.* 2001). So the relationships between the success of YOY fish (by species) and the presence of *B. longimanus* still need to be worked out. Open-water planktivores, such as alewife, herring, and shiners, will eat *B. longimanus* as adults while blue gills and sunfish which are associated with vegetation, avoid them (Coulas *et al.* 1998; Compton and Kerfoot 2004).

Invertebrate predators are also affected. Nordin (2005) studied 7 Muskoka lakes with mysids, of which 4 had *B. longimanus* populations. In her lakes, the presence of *B. longimanus* did not affect the growth rates of *Mysis relicta* (the opossum shrimp), a competitor and predator of *B. longimanus*, but decreased the rate of lipid accumulation which is needed for the animals to mature and reproduce. Mysid populations in the invaded lakes were smaller than those in the non-invaded lakes raising the possibility that mysid populations may be depressed by *B. longimanus*. Descending the food web, Hovius *et al.* (2006) found that the rotifer community was altered: *Conochilus unicornis* become dominant in invaded lakes in the Muskoka region. Laboratory experiments indicated that *B. longimanus* did not consume rotifers, and therefore, that the shifts results from indirect impacts of changes in other predators or competition.

Assessment Endpoint

"Maintenance of the native zooplankton species richness in the presence of *B. longimanus*".

At this point, insufficient information exists to include the fish community when setting assessment endpoints. In the future, any Risk Assessment of the impact of *B. longimanus* on lakes, especially where management options are being considered, needs to be expanded to include the fish community. This is discussed further in the section on establishment.

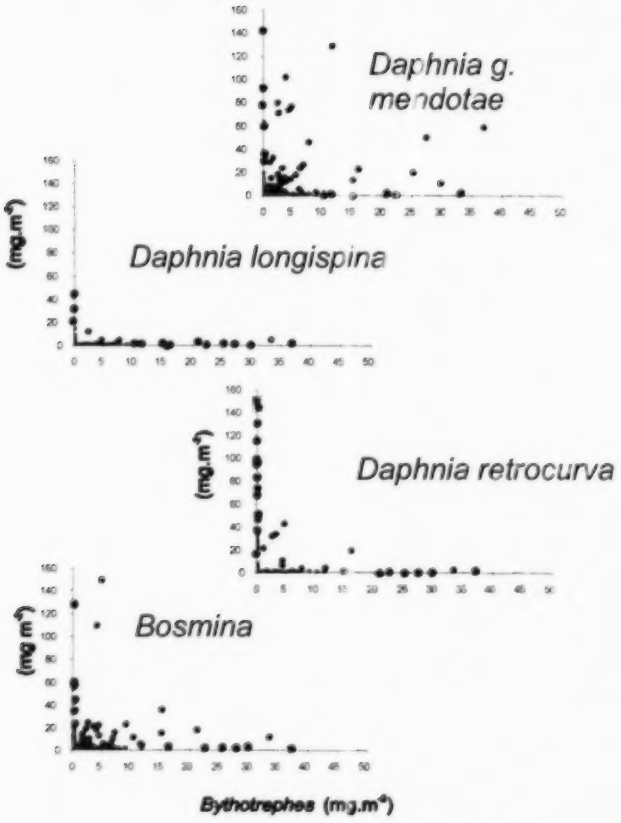

Figure 1. Relationships between the biomass of prey in the water column and that of *B. longimanus* in Lake Erie: June to Sept. 1992-1996. Data from whole water column tows (110-um mesh, 50-cm diameter net) in the eastern and central basins. (Johannsson and Graham, Fisheries and Oceans, Canada, unpublished data)

Measurement Endpoints

Measurement Endpoints can be selected along the gradient of *B. longimanus* impact on the zooplankton community.

1. No *B. longimanus* present - good
2. Few *B. longimanus* present, other cladoceran prey species present with normal biomass - good
3. Few *B. longimanus* present, most cladoceran prey species present but with reduced biomass - intermediate
4. Noticeable *B. longimanus* present and species richness depressed - bad

Biological Synopsis

A great deal of information on the distribution, life history, reproduction, growth, diet, predators and impacts of *Bythotrephes longimanus* are known from the literature and reviewed on the net (e.g. http://invasions.bio.utk.edu/invaders/flea.html)

Environmental Distribution

B. longimanus' native range has been obscured by extensive spread in Europe through out the last century and it is now broadly distributed through northern Europe and Asia (Fig. 2) (Gigorovich *et al.* 1998). It invaded the Laurentian Great Lakes of North American via ballast water sometime before 1982: a single individual was found in a zooplankton sample in Lake Ontario at that time by Dr. Hans Frikker (Johannsson *et al.* 1991; Berg and Garton 1994). The source population for the Great Lakes came from Lake Ladoga which is connected to St. Petersburg Harbour on the Baltic Sea: Lake Ladoga is the end point of a migration route which starts in the Ponto-Caspian region. The present genetic diversity of individuals in the Great Lakes, which is now similar to that of European populations, suggests that it has invaded a number of times from Lake Ladoga (Berg *et al.* 2002).

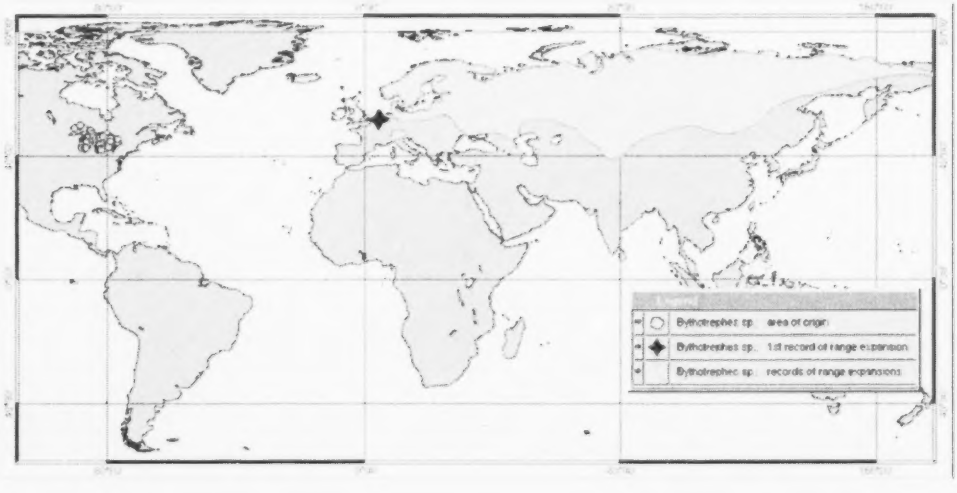
Bythotrephes sp. - area of origin
Bythotrephes sp. - 1st record of range expansion
Bythotrephes sp. - records of range expansions

Figure 2. World-wide distribution of *Bythotrephes longimanus.* Map was taken from http://www.zin.ru/projects/invasions/gaas/bytlon_w.htm

In its Eurasian range, *B. longimanus* inhabits water bodies ranging from ponds to large lakes, occurring most frequently in the deeper regions of large lakes and reservoirs. Although it has been found on occasion in abundance in meso-eutrophic conditions, it is normally associated with oligo- and meso-oligtrophic waters. In some lakes and reservoirs, it undergoes large diel vertical migrations, presumably to avoid predation. Such populations centre themselves in the metalimnion, or just above the metalimnion, during the day and move into the epilimnion at night (Grigorovich *et al.* 1998; Pangle and Peacor 2006; Pangle *et al.* 2007). This behaviour accords with their wide temperature tolerance (4°C to 30°C) and preference (10°C to 24°C) (reviewed in Grigorovich *et al.*

1998). This eurythermal trait permits them to capitalize on much of the ice-free season for growth and invasion in northern lakes. Drake *et al.* (2006) compared the impact of demographic stochasticity, environmental variability (stochasticity) and seasonal windows of invasion, based on temperature, of *B. longimanus* populations in eight invaded North American lake-years. They found that the temperature window of invasion was more important in determining establishment than either of the other two variables.

Other environmental gradients may also influence the distribution of *B. longimanus*. It is found under a wide range of conditions and Grigorovich *et al.* (1998) suggest that local populations may become adapted to extremes. *B. longimanus* is more commonly present if the pH of the lake is circumneutral (6.8-8.6) and the salinity is low (0.04-0.06‰) (Grigorovich *et al.* 1998). It infrequently occurs in brackish waters of 0.5-0.8‰. In the extreme, it has been found in water bodies with a pH as low as 4.0 and others with a salinity as high as 8.0‰. *B. longimanus* also occurs in lakes with a wide range of humic matter ranging from clear water to highly stained, and has been observed in swamped lakes in Byelorussia (reviewed in Grigorovich *et al.* 1998). With such a broad range of acceptable environmental conditions for survival, *B. longimanus* is well suited to invade many northern lakes which themselves include a wide range of pH and humic conditions as well as a wide range of maximum summer temperatures, largely dependent on depth and latitude.

Life History

The life history and reproduction of *B. longimanus* is typical of other cladocerans in that the populations are composed of females which reproduce parthenogenically for the majority of the season. Under stimuli from photoperiod, crowding and/or adverse environmental conditions, female cladocerans will produce males (Carvalho and Hughes 1983; Rose *et al.* 2002). Sexual reproduction ensues with the formation of resting eggs which will remain dormant until the following year. *B. longimanus* resting eggs hatch at water temperatures from 4°C to at least 10°C. Neonates (instar 1) weigh between 20 and 150 ug dry weight at birth (Sullivan and Lehman 1998; Branstrator 2005) and possess a pair of lateral barbs on the tail spine: an additional pair is added at each of the next two moults. The spine and barbs act as an anti-predator defense. Usually *B. longimanus* matures at instar 3 with a dry body weight of 97 to 289 ug (Branstrator 2005): animals do not continue to grow but do moult with the release of each clutch of young, but they no longer add barbs to the tail spine. The tail spine of the first instar is not kinked which lead to many problems with species identification; however, these have now been resolved genetically (Yan and Pawson, 1998; MacIsaac *et al.* 2000; Berg *et al.* 2002). Growth and egg production are temperature related: they reach maturation in 9.2 days at 12.7°C and 5.4 days at 21°C, and produce their first set of young after only 14 to 9 days at 12.7 °C to 21 °C. *B. longimanus* will reside in the epilimnion if possible, presumably capitalizing on the higher food levels and warmer temperatures in this thermal layer. The population grows very slowly in the spring until the water warms to 20°C: its development time is fastest between 20°C and 25°C (Garton *et al.* 1990). Bioenergetic models have been developed for *B. longimanus* (Lehman and Caceres 1993; Yurista and Shulz 1995). B. longimanus can consume more than 100% of its body weight a day and it has a net growth efficiency between 21% and 27%. When the *B. longimanus* population is kept under control it consumes 6% to 12 % of zooplankton production (Johannsson *et al.* 1999), when it establishes in a lake it will consume more

than projected estimates of zooplankton production when it reaches maximum densities (e.g. Dumitru *et al.* 2001).

QBRAT: INITIAL CONDITIONS

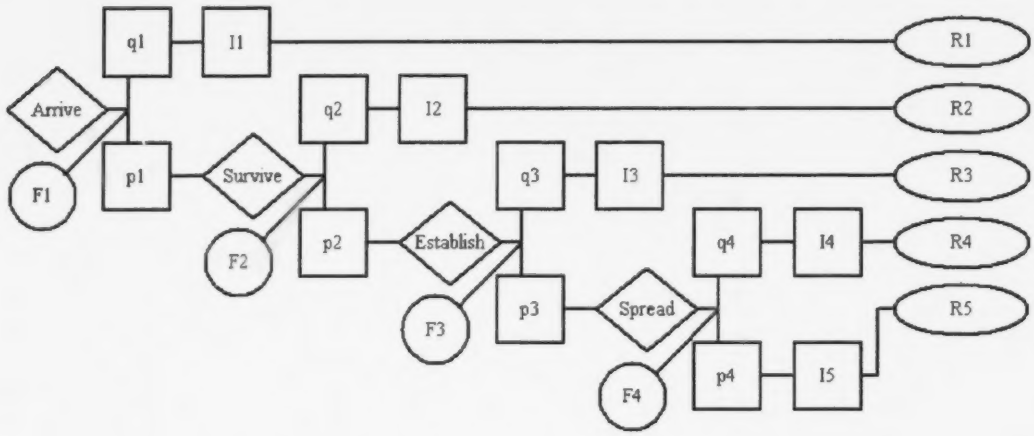

Figure 3. The diagram outlines the structure of problem solving undertaken by the QBRAT Tool. The four key steps in the colonization/invasion process are represented by diamonds. At each step, the square boxes contain the probability of the step occurring (ps) or not occurring (qs). Impacts of the events occurring up to each step and then not proceeding are represented by the squares containing 'I(n)'. For instance, if a species arrives but does not survive in the new environment, the impact is represented by I2 and any risk (to the environment or economy, depending on how you frame the impacts) that that evident incurs is calculated by the product of I2, Q2, and P1, which equals R2. All risks (R1 to R5) are summed to give the total biological risk of a species. The circles containing the 'Fs' represent costs to society to take management actions at each step.

I assumed that the value of impacts put into the QBRAT model would vary between 0 and 1. However, there was no guidance in the range that should be used - a standard range would enable comparisons between risk assessments – nor was there guidance in how to score various types of impacts. The workshop participants discussed the problems related to impacts in detail. In the meantime, I set up the present risk assessment to determine the risk of establishment of *B. longimanus* with high impact on the zooplankton community (impact = 1), in Muskoka lakes in the 2EB watershed. To examine other levels of impact, QBRAT would need to be set up and run again including the conditions that would lead to each of the other levels of impact.

Our risk assessment question addressed the probability of establishment in a set of lakes in 2006. In order to do this, I needed to determine the probability for individual lakes and then extrapolate to the watershed. The four diamonds representing the key steps in the invasion process (Fig. 3) were changed to "Arrival", "Survival of the Individual", "Establishment related to propagule pressure" and "Establishment related to mortality". Given this approach, I set Impacts 1, 2, 3, and 4 to '0', and impact 5 to '1'; that

is, *B. longimanus* arrived and the impact was 'Bad'. Risk is the product of probability and impact. In this way, I did not actually quantify the level of risk of damage to the ecosystem (however that would be quantified) but directly determined the risk of establishment of 'bad' scenarios.

Other than the efforts undertaken by the Ontario Federation of Anglers and Hunters (OFA) and the Ontario Ministry of Natural Resources (OMNR) to encourage lake users to clean their boats and tackle when moving between lakes, there are no estimates of management costs. Therefore, F2 to F4 were set to '0'. F1 was estimated at 50K to include the *B. longimanus* monitoring program and prevention activities. In the future, this cost could be evaluated against compliance and risks of establishment.

In developing this risk assessment, I further examined the implication of scale on lake accessibility; that is, does lake accessibility scale logarithmically or linearly and how would that affect the invasion process. And I examined the impact of varying levels of compliance by fishers with respect to gear cleaning, on the invasion rate.

QBRAT: Supporting Evidence

Arrival

Factors Influencing Arrival:

Accessibility of the lake

- Distance of lake from the road
- Distance to population centre

Transmission factors

- Probability of fishing an infected lake
- Compliance with cleaning of gear and boats
- Match of seasonal patterns - *Bytho* populations and fishing

Factors affecting the rate of spread of *Bythotrephes* are recognized to be key elements in understanding its threat to North American Lakes. J. Muirhead and J. Borbely from Dr. Hugh MacIsaacs laboratory (University of Windsor) have been developing gravity spread models to predict the spread of the invasion. The Canadian Aquatic Invasive Species Network (CAISN) 500-lake survey, lead by Dr. Norm Yan (York University), examines relationships between propagule pressure, indexed by lake accessibility, lake size and connectedness on establishment patterns. The present risk assessment draws on these data to roughly explore two algorithms for lake accessibility. More in depth analyses will be undertaken by Brian Leung of McGill as part of the CAISN Network deliverables. Norm Yan, Allegra Cairns and Melissa Elliot provided the data for the 2EB tertiary watershed (Muskoka Region) which was used to define representative Muskoka conditions of accessibility.

Lake Accessibility

Lake Accessibility (for each lake) was considered to be the product of the distance of the lake from an all-season road and from the nearest town. Each distance was weighted by a function which depicted human behaviour along the distance gradient (Fig. 4). Our principle assumption, in the weightings, was that people are lazy and generally short of time.

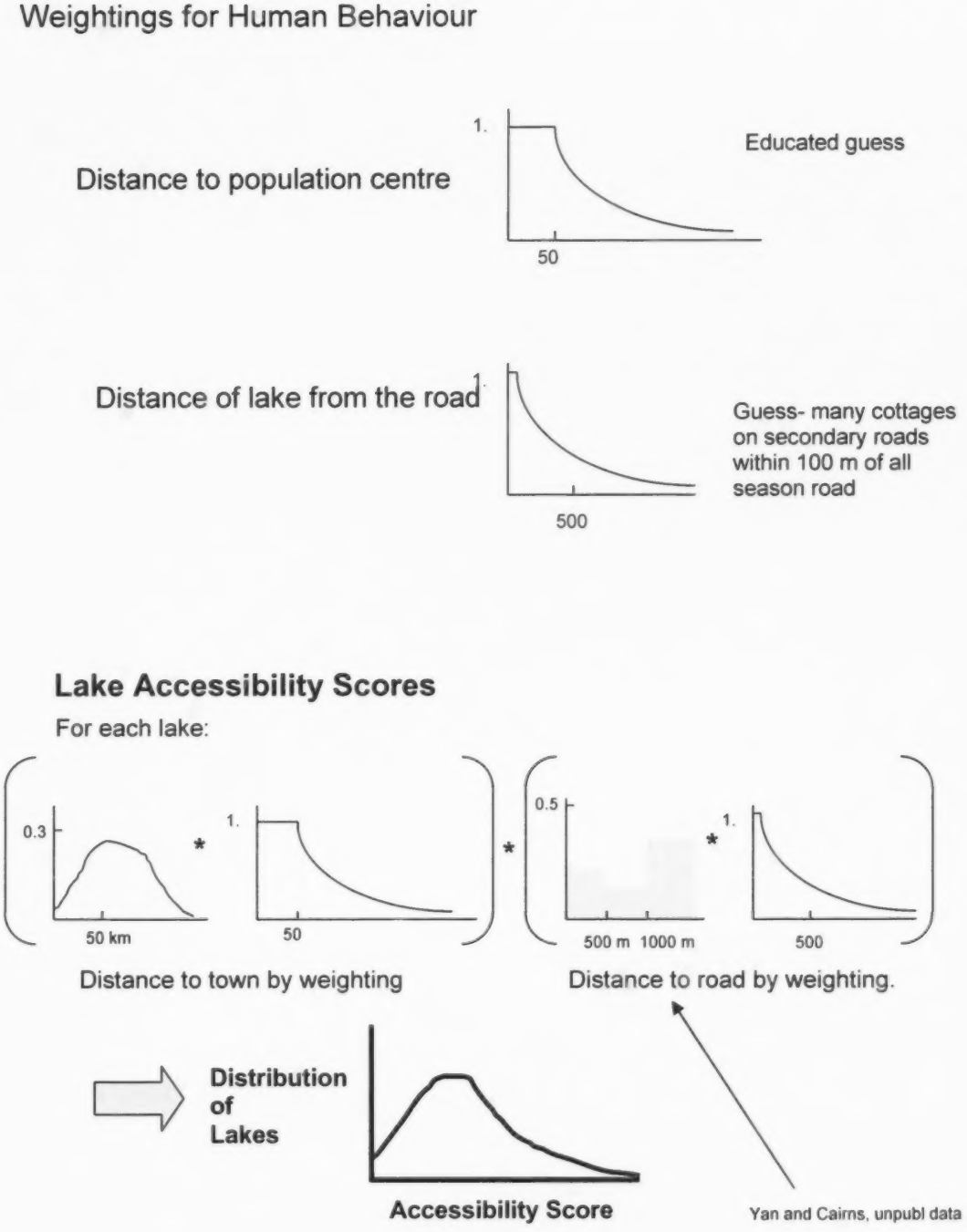

Figure 4. Conceptual models and data that would be used to develop Accessibility Scores for individual lakes in the Muskoka Region (2EB watershed).

Weightings for distances from roads: I assumed that most cottages on lakes were within 100 m from an all-season road; therefore, any lakes within that range were 100% accessible. The weighting function decreased logarithmically beyond that distance.

Weightings for distances from towns: I assumed that fishers would readily travel half an hour or 50 km from a town to fish. Thus lakes within this circumference were 100% accessible. Again the weighting function decreased logarithmically beyond that range.

Lakes were divided into three accessibility categories – high, medium and low. The proportion of lakes in each category was taken from the proportion of lakes >1 ha surface area in the 2EB watershed. Without actual data, I assumed that 0.25 of the lakes were highly accessible, 0.22 had medium accessibility scores and 0.53 had low accessibility scores.

Transmission Factors

- Geographical probability of infection for each lake.
  Probability of going to an infected lake and then going to an uninfected lake.

- Compliance with cleaning of gear and boats
  Information from OFAH and OMEE – 60% ± 10% (CL = guess)

- Match of seasonal patterns
  Overlap in timing of *B. longimanus* seasonal population maxima or larger populations and the distribution of fishing trips

For each lake, the probability of arrival is the product of the probability of a fishing trip carrying *B.longimanus* and the probability of a fishing trip going to the lake in question. In order to estimate the probability of an infected fishing trip, I assumed that all invaded lakes fell in the group of lakes with high accessibility scores. In watershed 2EB, our representative watershed, 25% of the 1636 lakes fall in this category. There were 30 known invaded lakes in this watershed in 2005 (Cairns *et al.* 2006); that is, 2% of all lakes. If I assume that all invaded lakes occur in the high accessibility category, they constitute 7.6% of the highly invasible lakes. If lake accessibility follows a logarithmic decline across the three lake accessibility categories, then 90% of all fishing trips occur in the High Access category of lakes. Therefore, 6.8% (0.076*0.90) of all fishing trips go to invaded lakes. If the accessibility scale is linear, then it would represent 4.6% of all fishing trips.

The question is what proportion of these contaminated boats will take their cargo to non-invaded lakes. According to the 2004 angling survey by OMNR, 50% of the boats do not move between lakes (Brownson, OMNR, unpubl. data). Therefore the following calculations apply only for boats that are mobile. Following the above reasoning, for the logarithm access scale, 90% of trips will return to the highly accessible lakes and 7.6% of these trips will go to lakes which are already invaded; that is, 0.5% (0.068*0.90*0.076) of all fishing trips. 6.3% of all fishing trips would potentially carry *B. longimanus* to new lakes the next trip. The Federation of Anglers and Hunters has run an extensive advertising campaign encouraging people to pressure clean their boats, bait wells, and

anchor and fish lines when moving their equipment between lakes. They estimate 60% compliance. I investigated the effect of compliance between 40% and 80% on the number of newly infected lakes the following season. I assumed 10,000 fishing trips per season with half of them confined to one lake, leaving 5000 mobile fishing trips per season.

Table 1. Determinations of the probabilities of a new lake being infected in each of the three Lake Access Categories under different levels of compliance with gear-cleaning regulations for inter-lake trips. Lake accessibility distribution: 0.25 (high), 0.22 (medium), and 0.53 (low). Compliance in angler surveys (1998, 2004) was 60% (Francine MacDonald, OFAH; Beth Brownson, OMEE, unpubl. data). 90% of all fishing trips represents a logarithmic decline in lake accessibility scores amongst the three categories of lakes, while 60% represents a linear decline in the access scores. I assumed 10,000 fishing trips per season with 50% of them confined to one lake.

Compliance: Gear Cleaning between lake	Fishing Trips to High Access Lakes	Lake Access Score	Probability of a Fishing Trip to Lake$_{(n)}$	No. of fishing Trips in Infective Period	Probability of gear being Infected	Probability of a new lake being Infected	CL%
80%	90%	High	0.002204	5000	0.0127	0.140	80
		Medium	0.000220	5000	0.0127	0.014	130
		Low	0.000022	5000	0.0127	0.001	220
	60%	High	0.001457	5000	0.0087	0.063	80
		Medium	0.000801	5000	0.0087	0.035	130
		Low	0.000146	5000	0.0087	0.006	220
60%	90%	High	0.002204	5000	0.0255	0.281	80
		Medium	0.000220	5000	0.0255	0.028	130
		Low	0.000022	5000	0.0255	0.003	220
	60%	High	0.001457	5000	0.0174	0.127	80
		Medium	0.000801	5000	0.0174	0.070	130
		Low	0.000146	5000	0.0174	0.013	220
40%	90%	High	0.002204	5000	0.0382	0.421	80
		Medium	0.000220	5000	0.0382	0.042	130
		Low	0.000022	5000	0.0382	0.004	220
	60%	High	0.001457	5000	0.0261	0.190	80
		Medium	0.000801	5000	0.0261	0.105	130
		Low	0.000146	5000	0.0261	0.019	220

The probability that a boat or gear will become contaminated will also depend on the overlap between fishing pressure and the seasonal pattern in *B. longimanus* population growth and maxima. Although the population dynamics of *B. longimanus* can vary between lakes, the maximum population generally occurs between late June and early August. Therefore fishing trips during this period are most likely to become contaminated. In the section on establishment, I investigate the requirements to

establish a *B .longimanus* population and estimate the impact of season on the proportion of infected fishing trips.

In summary, the probability of arrival at any specific lake would be related to its relative accessibility score, the number of fishing trips, and the percentage of trips carrying *B. longimanus.*

$$\text{The probability of a fishing trip to Lake}_n\text{ (PFT)} = \frac{\text{Lake}_n\text{ Accessibility Score}}{\Sigma\text{ Accessibility Scores for all Lakes}}$$

Probability of Infection of Lake_n = No. Fishing Trips * Percent Infected * PFT to Lake_n.

I investigated the effect of lake accessibility, the scaling of lake accessibility and the level of compliance on the probability of infecting a lake in each of the three lake accessibility categories (Table 1).

Some notable gaps which I did not consider in these estimations were:

1. Transport between lakes by research gill nets (Francine MacDonald, OFAH)
2. Transport between lakes due to connectivity (Presently investigated by Norm Yan, York University)
3. Transport between lakes by the gut contents of bait fish moved between lakes
4. Transport of resting eggs by wild fowl when they fly
5. Importance of access by all terrain vehicles (Nick Mandrak, DFO)

Survival

A comparison of the range of environmental conditions experienced by successful *B. longimanus* populations in Eurasia suggests that *B. longimanus* will not be limited by its environmental requirements from establishing in all Muskoka lakes (Table 2). The probability of survival was assigned a value of '1'.The only concern is the decreasing calcium concentrations observed recently related to acid deposition and forestry depletion of base cations from Shield watersheds (Keller *et al.* 2001; Watmough and Dillion 2003). Dr. Norm Yan is presently working on this assessment.

Table 2. A comparison of the environmental conditions of *B. longimanus* habitat in Eurasia (reviewed by Grigorovich *et al.* 1998) and Muskoka Region environmental lake data (Nordin 2005, http://www.on.ec.gc.ca/wildlife/acidrain/ar-intro-e.html, Muskoka Watershed Report Card (net 2005))

Environmental Condition	Eurasia	Muskoka Region
Lake Depth	ponds to large lakes	Considering lakes ≥1 ha
Temperature*	4°C – 30°C	4°C – mid 20's
pH	4.0 – 8.6	5.5 – 7.0
DOC – colour	clear to highly coloured	2 – 12 $mg.L^{-1}$
Trophic Status	oligotrophic - eutrophic	Oligotrophic to barely eutrophic

*resting eggs not considered

Establishment

The ability of an invader to establish in a new lake is determined by the balance between population growth potential and mortality rates. I examine both aspects of the equation to try to determine the probability of a potential successful establishment based on growth rates and then the likelihood that predation will overcome that population.

In Muskoka lakes, *Bythotrephes* depend on zooplankton as prey and compete with macroinvertebrates, namely, *Mysis relicta*, and *Chaoborus* spp., as well as planktivorous fish. Growth will depend on the level of food resources and temperature while mortality will depend on the abundances of predators and potential refuges from predation (Fig. 5).

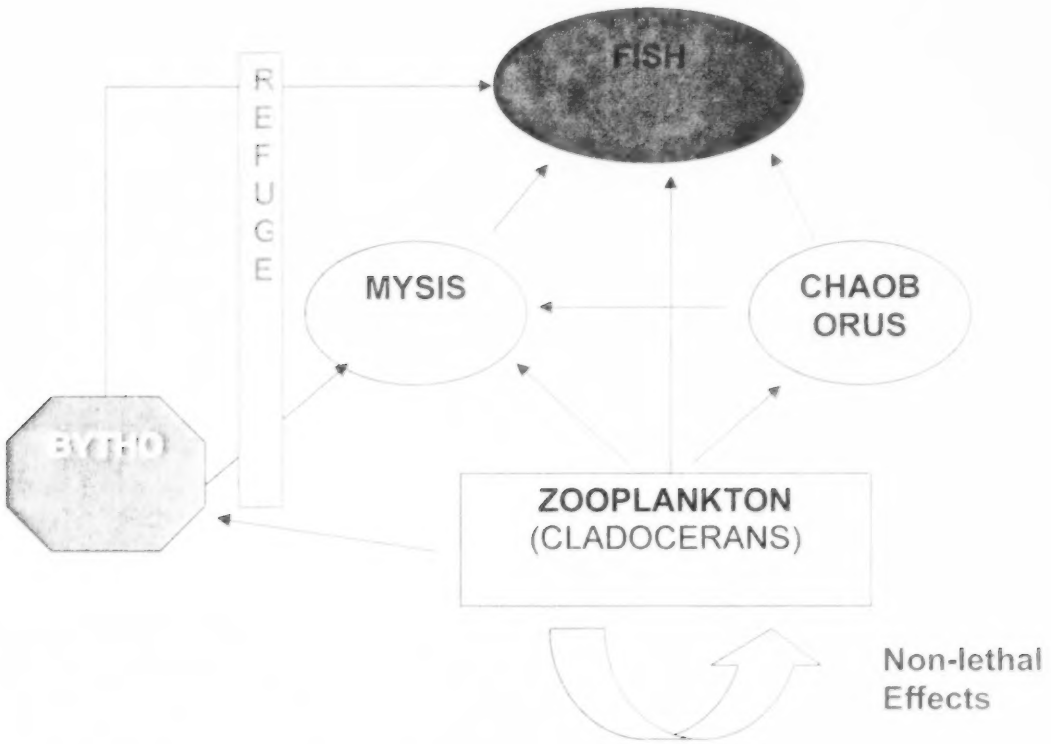

Figure 5. Conceptual model of the main participants in the food web directly associated *Bythotrephes longimanus*. Refuges may be critical to establishment. Non-lethal effects on zooplankton may depress zooplankton productivity available to the predatory species.

Growth

Whether a population will establish depends on attaining a minimum sustainable fall population (SFP). The size of this population is determined by (1) the need to have sufficient animals that they can meet for sexual reproduction to produce resting eggs, and (2) the size of the egg bank needed to start a sustainable population the next spring.

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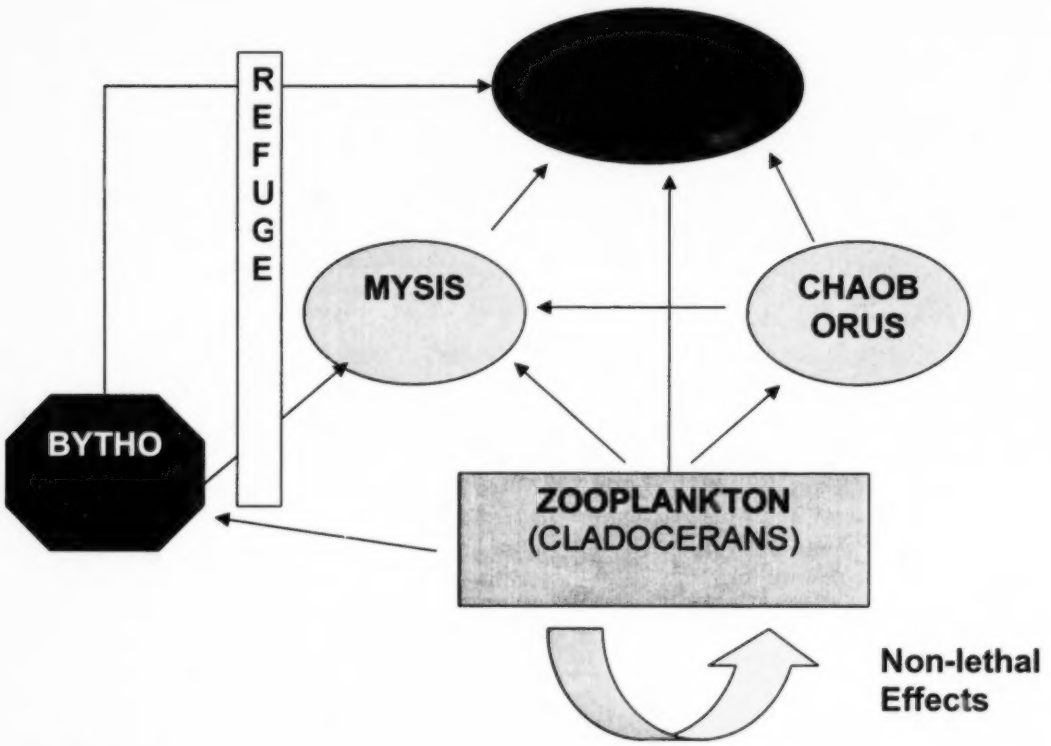

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Several different lines of evidence were evaluated in order to estimate a minimum sustainable fall population.

One estimate of the minimum sustainable fall population comes from densities of *B. longimanus* observed in the fall. Densities from four inland lakes in late September were always >2 individuals.m^{-3} (Yan and Pawson 1997; Nordin 2005).

I do not know the density of *Bythotrephes* needed for sexual reproduction. In other cladocerans, sexual reproduction is associated with high densities, low food supplies and certain photoperiods (Rose *et al.* 2002). In *Daphnia magna* the minimum population density for sexual reproduction was 400,000.m^{-3}. Densities this high are unheard of for *Bythotrephes*; however, *Bythotrephes* is larger than *Daphnia magna*, its distribution is generally very patchy and it has been observed to 'school'. Windrows of *Bythotrephes* have been observed on beaches along the North Channel of Lake Huron. Wind may be very important in concentrating them and this will assist with sexual reproduction. Likely, this means that the minimum SFP for sexual reproduction is not as high as in *Daphnia*, but the need to find each other may drive the minimum density higher than that estimated from resting egg requirements.

Working backwards from the minimum observed fall population, I can also calculate the minimum number of resting eggs needed to produce that population, and the size of the population the previous fall that would be required to produce that number of eggs. This process requires information on population growth rates through the season: an equation predicting growth rate in inland lakes by Julian date (day of the year) was recently published by Drake *et al.* (2006).

$$r = 0.000000623x3 - 0.000479519x2 + 0.117841x - 9.13838, \text{ where } x = \text{Julian Date}$$

Data on the hatching rate of *B. longimanus* resting eggs in the laboratory suggested that at 4°C only 8% of the eggs would hatch while at warmer temperatures of 6°C to 10°C 49% would hatch (Yurista 1997). Lakes supporting Drake *et al.*'s (2006) growth rates need a minimum population of 5E-5 individuals.m^{-2} at the end of the first year to develop a sustainable population at the end of the second year (Table 2). Several of the lakes in their paper had much lower growth rates. I estimated the needed population for lakes with half the growth rate. In such lakes, a minimum 0.6 individuals.m^{-2} was required.

Table 2. Minimum fall population reached as a function of propagule pressure (inoculum size on July 1st), and of hatching rate of resting eggs. I assumed 4 resting eggs per female, a 1:1 sex ratio and 11% pregnancy rate (Harp Lake data, Anges Blukacz unpubl. data). The bolded values indicate the minimum inoculum and hatching rate required to reach the minimum sustainable fall population by Sept. 30th: italics (slow growth rate), plain (faster growth rate). See text for explanation.

	Inoculum Size on July 1st (no.m^{-3})				
Hatch Rate	1	0.1	0.01	0.001	0.00001
8%	56.818	5.682	***0.568***	0.057	**5.68E-05**
49%	9.276	***0.928***	0.093	**0.009**	9.28E-06

The next step is to determine the inoculum needed to obtain the different minimum population sizes. I determined population densities on September 30th from a range of inocula arriving through the summer season. The inocula were grown using both the predicted and 50% of the predicted growth rates (Fig. 6). At the higher growth rates, inocula of 1.0E-6.m^{-2} was sufficient to attain SFP, while at the slower growth rate inocula of 0.01 to 0.001.m^{-2} were sufficient in July and 0.01 to 0.1.m^{-2} were sufficient in August.

Thus, not all fishing trips to invaded lakes are equally likely to carry *B. longimanus* to a new lake in sufficient densities to start a sustainable population. From the above considerations, I assumed that all fishing trips to infected lakes could carry enough inoculum to successfully infect a new lake with high growth rates, but only inocula added in July to slow growth rate lakes would be successful. The other factor which influences establishment is the seasonal pattern in the distribution of fishing trips through the May to October fishing period. I speculate that during the July-August holiday season, more fishing trips occur in July than in August and the majority will occur in the last two weeks of July. *B. longimanus* populations are not consistently high during the season and usually peak between late June and mid August, maximizing the likelihood of a successful transfer to a new lake. To fully capture the potential establishment risk, one must integrate the seasonal pattern in fishing trips with the seasonal pattern in needed propagule pressure. I assumed that 50% of infected fishing trips would go to slow growing lakes and 50% to fast growing lakes, reducing the proportion of all fishing trips which could carry sufficient inoculum from 80% to 70% (Table 3).

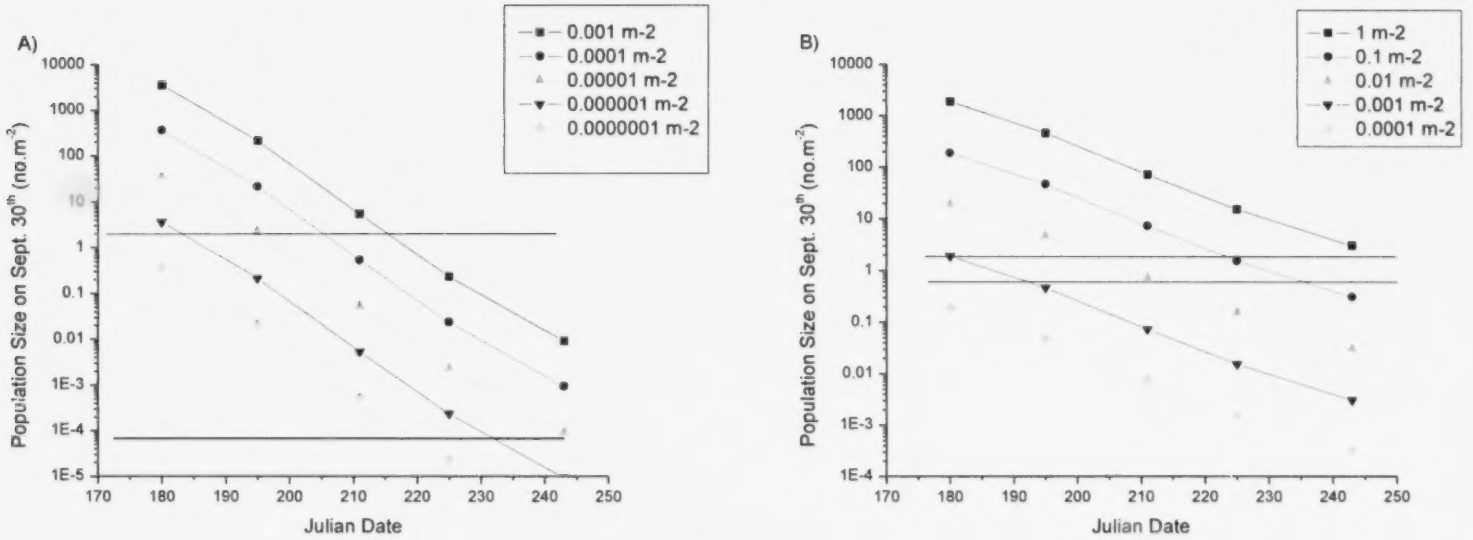

Figure 6. Predicted population size on September 30th given inocula of different concentrations introduced to the lake at two week intervals through the July and August period. A) Growth rates from Drake *et al.* (2006), B) 50% of the growth rates in A. The lower lines are the cut off levels for reaching the minimum sustainable fall population. The upper lines represent the observed autumn density in invaded lakes

Table 3. Result of seasonal distribution of fishing trips (FT) and propagule pressure on the proportion of infected fishing trips which might initiate a sustainable population of *B. longimanus*.

Month	Weeks	Seasonal Probabilities		
		Fish Trips	Infected FT will cause Establishment	Proportion of Total FT that could pick up sufficient inoculum
June	1-4	0.10	0	0
July	1-2	0.20	1.0	0.200
	3-4	0.30	1.0	0.300
August	1-2	0.25	0.5	0.125
	3-4	0.15	0.5	0.075
September	1-4	0.1	0	0
Total				0.70

I have arrived at the conclusions that for this risk assessment:

1. Long term sustainable populations have fall densities ≥ $2.m^{-3}$
2. Propagule pressure needed to reach that density in the second year is
   Reach from any inoculum during July and August in higher growth rate lakes
   Reach from any inoculum during July in lower growth rate lakes

I am assuming that:

1. 50% of all lakes are slow and 50% are high growth rate lakes
2. 80% of fishing trips occur in July and August but that of the infected trips during that time only 70% will reach lakes with sufficient propagule pressure to initiate a sustainable population.

Mortality

Factors affecting establishment success, are poorly understood (Drake *et al.* 2006). Community structure is hypothesized to be an important determinant as it encompasses predator/prey relationships and competition for resources. Disturbed habitats, where these relationships have been distorted and resources have become more available, are more likely to be invaded (Kolar and Lodge 2000). Thus community structure would appear to ward off a portion of invasions. For *B. longimanus*, the important components of the community would be its predators and competitors – fish, mysids and chaoborids. Refuges may also be important and allow colonization in the face of predation.

Many fish species will consume *B. longimanus* (reviewed in Grigorvich *et al.* 1998 and in Coulas *et al.* 1998). *B. longimanus* has a long, spined tail which helps to protect it from fish predation. The spine is very effective: early studies of Great Lakes' fish species found that most did not eat *B. longimanus* until they were >70 mm in total length (Barnhisel, 1991a,b; Barnhisel & Harvey, 1995: Branstrator & Lehman, 1996). The exceptions are bloater (*Coregonus hoyi*), alewife (*Alosa pseudoharengus*) and smelt (*Osmerus edax*) (Branstrator & Lehman, 1996; Parker *et al.* 2001). Thus many of the fish species which consume *B. longimanus* are adults, either planktivores or obligate planktivores, and many have shown a positive selection for *B. longimanus*. Some can depress *B. longimanus* populations; e.g. Swedish lakes (Stenson 1978 in Coulas *et al.*

1998), Russian lakes (Vekhov 1987 in Sikes 2002), Lake Ontario (Johannsson *et al.* 1991).

In Lake Ontario, where *B. longimanus* has been kept in check by the alewife population, zooplankton species richness was not altered by its presence (Johannsson *et al.* 1998). As mentioned in the introduction, *B. longimanus* also co-existed with a range of cladoceran species in Lake Erie in the early 1990s where it was kept in check by a large, hungry smelt population (Dahl *et al.* 1994; Graham *et al.* 1995). Furthermore, *B. longimans* was depressed below detection (or eliminated) in the western basin of Lake Erie between the 1980s and early 1900s (Johannsson *et al.* 1999).

Mysis relicta also preys on *B. longimanus* (Nordin 2005). Nordin hypothesized that, under some circumstances, it may be instrumental in controlling *B. longimanus* populations. She investigated 7 mysid lakes in the Muskoka Region, four of which contained *B. longimanus* and three of which did not. Two of the non-invaded lakes were coloured with shallow Secchi Depths to the extent that mysids were present in the water column during the day. In these lakes, *B. longimanus* will be preyed upon by fish in the surface waters and by mysids in the hypolimnion and lower metalimnion during the day as well as the night. With no physical refuge from predation, *B. longimanus* may not be able to establish a population.

Coulas *et al.* (1998) put forward the hypothesis that *B. longimanus* exists in the presence of selective predation from lake herring (*Coregonus artedi*) because the lake is partitioned thermally, which reduced the period of overlap between the two species. Thermal and light refuges have long been known to be important to herbivorous zooplankton as a mechanism minimizing predation. *B. longimanus* is known to undergo diel vertical migrations in some lakes in Eurasia and North American (Grigorovich *et al.* 1998; Pangle and Peacor 2006). Thus, it has the capacity to minimize its predation risk through the use of refuges. It is the lack of a refuge that likely led to its loss from the western basin of Lake Erie, which is shallow and does not stratify during the summer. It is the lack of a refuge in Nordin's lakes which is also thought to prevent their successful invasion.

Refuges can be defined by light penetration (Secchi Depth) and potential for thermal stratification. Nordin's (2005) uninvaded lakes had Secchi Depths of 1.7 and 2.1 m. I assumed that lakes with Secchi Depths ≤ 2.1 m lacked a refuge for *B. longimanus* if mysids were also present in the lake. I also assumed that all lakes with a maximum depth of 15 m would lack a sufficient thermal refuge. This was based on the expected depth for the bottom of the thermocline. Dadswell (1974) conducted an extensive study of lakes through out the Canadian Shield including the Muskoka region. He was testing hypotheses about the distribution of glacial relic species, including *M. relicta*. The proportion of lakes with refuges (Secchi Depths ≤ 2.1 m and/or maximum depths < 15 m) wwas determined from his Figure 5 (Table 4). The glacial history of the region also suggests that approximately 37% of the lakes should contain *M. relicta*: mysids were found in 263 out of the 355 lakes in glacial regions, approximately half of the area in the Muskokas had too high an elevation to be covered by the glacial lakes (Dadswell 1974, Map 3). Mysid generation time may also affect its ability to control *B. longimanus* and can range from one to two years (perhaps more) in Canadian Shield lakes. If mysids grow to maturity between spring and fall, the size of the animals in July and early August

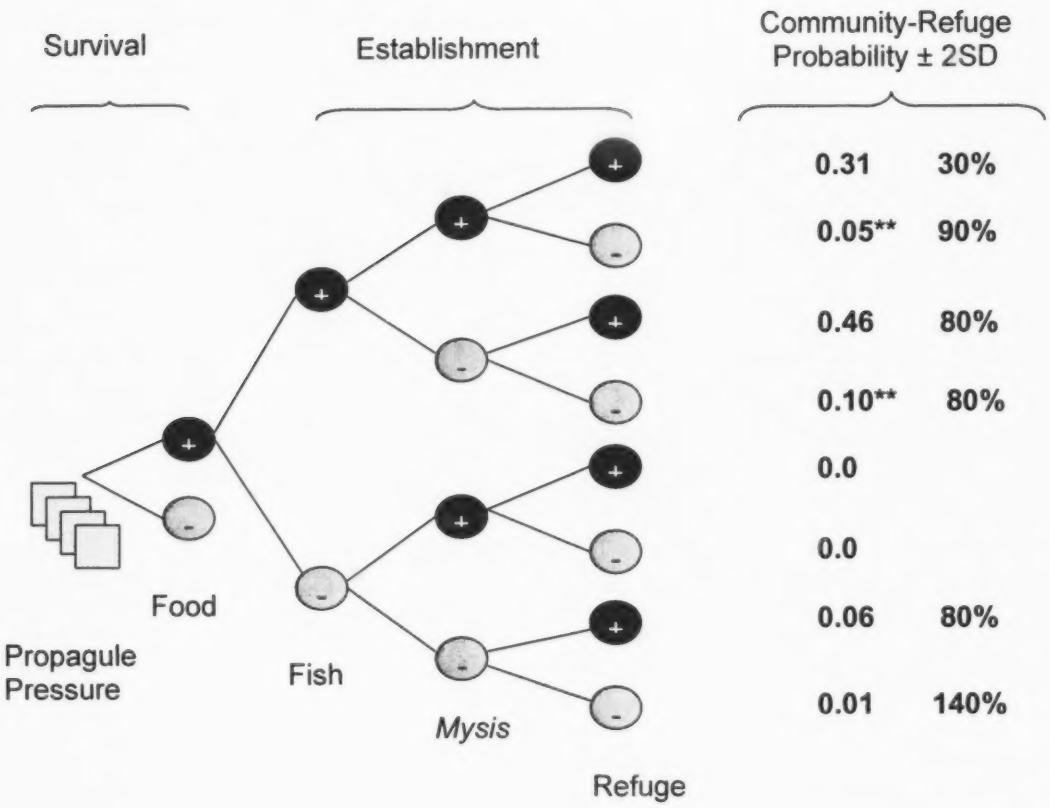

Figure 5. Decision tree representation of the possible community/refuge combinations that could occur in inland lakes. Blue circles indicate the presence of the condition and green the absence. Their proportionate representation, of all lakes in the region, are given to the right of the branch together with an estimate of the confidence limits.

would likely be too small to prey on *B. longimanus* or at least to prey on them effectively. Unfortunately, there has been no systematic survey of the range and distribution of life history characteristics of mysids in this region. A few lakes are known to have one generation a year (Adare and Lasenby 1994); however, the majority appear to support mysids with two generations (data from Nordin 2005 and Adare and Lasenby 1994). I assumed that only 10% of mysid lakes would have a mysid generation time of one year.

Table 4. Distribution of habitat conditions in Canadian Shield lakes that are related to refuges for *B. longimanus*.

Habitat Conditions	Proportion of Lakes	Confidence Limits
Secchi Depth > 2.1 m	0.85	10%
Secchi Depth ≤ 2.1 m	0.15	70%
Max. Depth ≥ 15 m	0.82	10%
Depth < 15 m	0.18	70%

In order to apply the concepts of the importance of community structure and refuges I constructed a decision tree based on the presence/absence of fish, mysids and refuges (Figure 6). The probabilities of the eight final configurations were determined from the probabilities of co-occurrence of their elements. In making these calculations I assumed 7% of all lakes were fishless, I recognized that lakes which did not contain fish would not contain mysids as the absence of fish only occurs in areas which were not covered by glacial lakes, and that lakes which lacked a hypolimnion were not likely to support mysid populations. Only the decision branches including fish and no refuges were thought to be impossible for *B. longimanus* to invade permanently. Of the other two branches including fish, I assumed that *B. longimanus* could be kept at low enough levels to prevent loss of zooplankton species richness in 4% of the cases. The summation of all these calculations suggested that 82% of lakes could be successfully invaded from a community/habitat perspective and 18% were unlikely to be invaded.

Impacts

The risk assessment determined that 82% of all lakes were likely to experience severe impacts of *B. longimanus* if invaded: only 18% would avoid invasion or support non-aggressive populations. I estimated the number of lakes that would be severely invaded in a year, based on the 2005 conditions in watershed 2EB in the Muskoka Region. If the scale of lake accessibility were logarithmic, projections predict 28 to 84 lakes would be invaded, depending on the level of compliance (Fig. 6). That rate of invasion would be nearly half if the scale were linear. The impact of compliance was significant: roughly a third the number of lakes are invaded at 80% compliance compared with 40% compliance.

More lakes were estimated to be invaded than would seem reasonable considering the present rate of invasion. Sensitivity analyses indicate that the projections of newly invaded lakes were most sensitive to the value of P1 (arrival), and this sensitivity increased as lakes became less accessible (Fig. 7). High access lakes were equally sensitive to the seasonal patterns in boat traffic (P3): this factor decreased as the sensitivity of P1 increased.

One particularly weak estimate was the determination of needed propagule pressure: calculated minimum densities seemed to be awfully low. At this point, I have not accounted for the minimum density needed for sexual reproduction and this may be the key. In exploring this problem, the physical dynamics of the lake need to be taken into account. If the needed inoculum were higher, then less of the season could be used to transfer animals from invaded to non-invaded lakes. This could significantly decrease the number of new invasions. This work would address P3.

Nor do I have an estimate of the real number of fishing trips per season or their distribution which addresses P1. The accessibility scores for lakes were not fully parameterized and were dealt with as three categories rather than a continuous distribution. Improvements here may alter the results and conclusions as well (P1).

QBRAT – Possible Improvements

Good process for structuring a problem and determining where to put effort

- both the Monte Carlo simulation results and summary file very helpful to explore scenarios and understand the confidence range.

Considerations

QBRAT- variables must be independent

- can not implicitly handle inter-relationships amongst Variables thus must deal with them outside of the formal framework

QBRAT – handles only one set of conditions

- to deal with more complex situations one needs to create multiple scenarios which are run through QBRAT separately and which need to be weighted by frequency of occurrence of those cases

QBRAT – handles one location of arrival

- thus when looking at establishment in a region, must look at the arrival at each lake and work up
    - probability category needs to be run through QBRAT and final outcomes weighted by proportion of lakes in that category and all data summarize

As one will run a number of QBRAT variations to look at changes in sensitivity, risk and costs with different management actions:

1) possibility of sequentially numbered reports
2) possibility of having an input run program and output file

How do you deal with Confidence Limits when the probability is >1?

Costs – the program assumes that each event will initiate a cost

- what happens to preventative costs – should not be multiplied by ps

Report:

Have the option of having the report come up on your screen immediately

Separate the 'p=' and numeric value so the values can be rapidly copied and transferred to another program.

Display 3 decimal values in the probability windows

Put the 0.3 probability line on the sensitivity graph

Manual:

Include impacts of settings, and settings to test certain hypotheses.

Number of Invaded Lakes

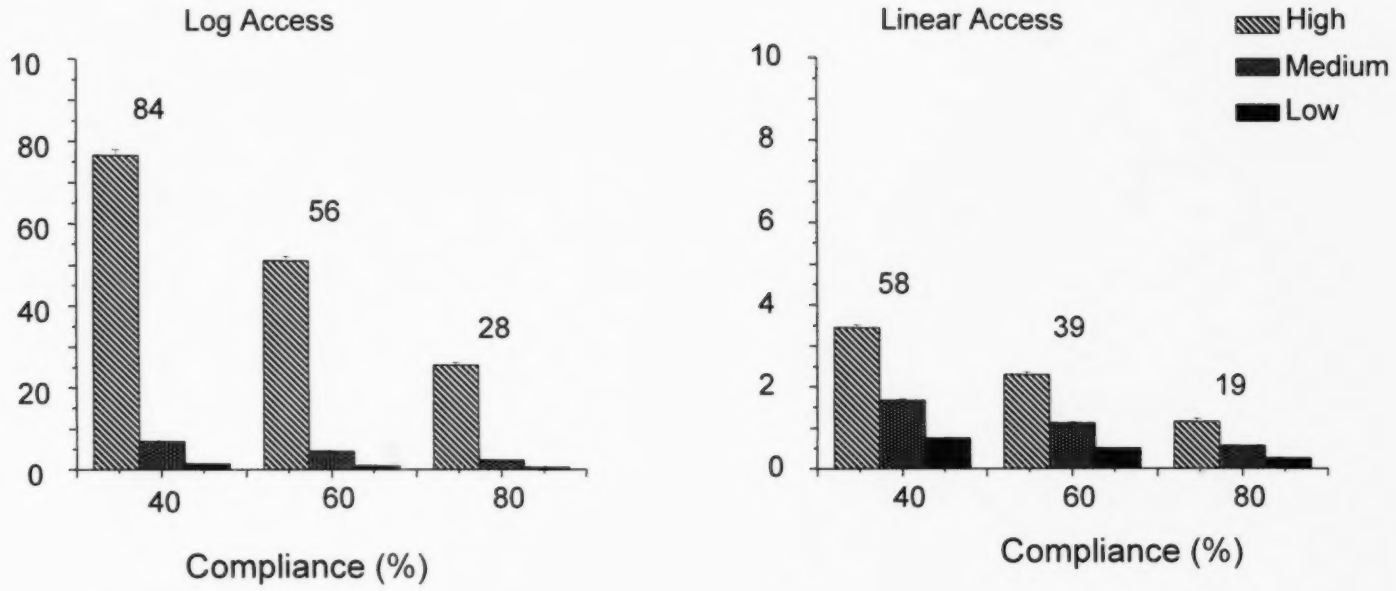

Figure 6. Predicted number of lakes in the 2EB watershed that would be invaded successfully, with high impact to the zooplankton community, in 2006 in three lake accessibility categories (High, Medium and Low) at three levels of compliance. Compliance involves cleaning of boats and gear when moving between lakes. The Lake Accessibility Scale is assumed to be logarithmic in the left panel and linear in the right panel. (with high impact to the zooplankton community)

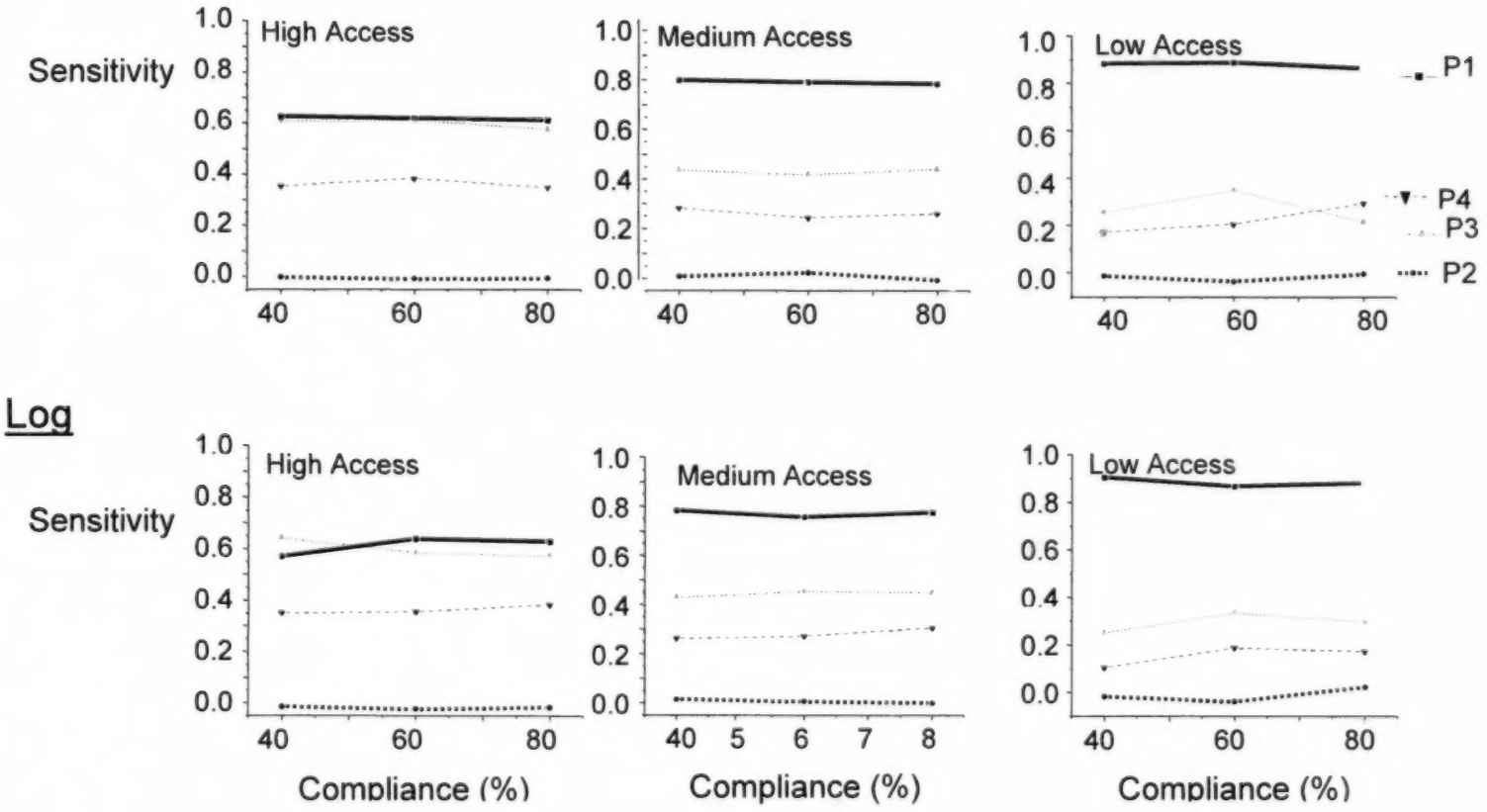

Figure 7. Changes in sensitive of P1 (arrival), P2 (survival), P3 (establishment-growth) and P4 (establishment-mortality) with compliance, lake accessibility and the scale of lake accessibility.

Acknowledgements

This Risk Assessment on *Bythotrephes longimanus* has greatly benefited from discussions on invasion biology and *B. longimanus* biology with Sarah Bailey, Agnes Bulkacz and Marten Koops. I would also like to thank Agnes Bulkacz, Norman Yan, Allegra Cairns, Melissa Elliot, Francine MacDonald and Beth Brownson for providing unpublished data to help bound the exercise.

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